Stellar Coronae in the Chandra and XMM-Newton Era
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XMM-Newton Probes the Solar Past: Coronal Abundances of Solar Analogs at Different Ages

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Abstract. We present an X-ray spectral analysis of four solar analogs with different ages and magnetic activity levels. We find largely different coronal compositions. The most active stars tend to show an "Inverse First Ionization Potential" (IFIP) effect, i.e., elements with low FIP are underabundant. Less active stars tend to the opposite effect, with relative overabundances of low-FIP elements. Equivalent Chandra results are presented that support these results.

1. Introduction

Previous X-ray observations provided evidence for anomalous elemental compositions of active stellar coronae when compared to the solar photosphere. Spectra from many active stars reveal significant underabundances of most accessible elements (Drake 1996). This contrasts with the typical solar coronal composition that shows enhancements of elements with a First Ionization Potential (FIP) below 10 eV, typically by factors of about 4 relative to high-FIP elements and hydrogen (Feldman 1992). On the other hand, spectra from inactive stars revealed either no abundance anomalies, or evidence for a solar-like FIP effect (Drake, Laming, & Widing 1995, 1997), suggesting systematic abundance differences in the two classes of stars (Drake 1996).

New grating spectra, obtained with *XMM-Newton*, have added a new riddle to coronal abundance studies. Deep observations of HR 1099 (Brinkman et al. 2001, Audard, Güdel, & Mewe 2001), AB Dor (Güdel et al. 2001a), and YY Gem (Güdel et al. 2001b) showed characteristic underabundances of low-FIP elements such as Fe, Mg, and Si relative to high-FIP elements such as C, N, and O, with the highest-FIP element Ne showing the highest abundance. This pattern, dubbed the "Inverse FIP Effect", challenges previous models devised for the element fractionation in the (solar) chromosphere. A high Ne/Fe abundance ratio in HR 1099 has been confirmed by *Chandra* as well (Drake et al. 2001). Since the coronal material ultimately derives from the photosphere, a physically interesting result should relate the coronal composition to the photospheric mixture of elements, which is often unknown. The stars we investigate here, in contrast, are known to be of solar photospheric composition.

2. Targets and Analysis

Our two least active stars, π^1 UMa (G1 V) and χ^1 Ori (G0 V), are both members of the Ursa Major Stream, with an estimated age of $\sim$300 Myr (Dorren & Guinan 1993). Stars in this stream are of near-solar composition (Soderblom & Mayor 1993), supported by the measured [Fe/H] values of our targets (Cayrel de Strobel et al. 2001). EK Dra (dG0e), a Zero-Age Main-Sequence (ZAMS) star with an age of $\sim$100 Myr, is a kinematic member of the Local Association, a stellar group with solar photospheric metallicity (Eggen 1983). To study activity at its extreme, we added the active ZAMS star AB Dor (Pakull 1981) to our sample, despite its somewhat later spectral type of K0 V. It represents saturated activity and is also a member of the Local Association, with a measured photospheric metallicity [M/H] $\approx 0.1 \pm 0.2$ dex for Al, Ca, Fe, and Ni (Vilhu et al. 1987).

XMM-Newton (Jansen et al. 2001) observed our targets for $\approx 36-59$ ksec each. All data were analyzed following standard procedures within the SAS software. We principally used the high-resolution RGS data (den Herder et al. 2001), with a spectral resolving power of 100$-$500 in the bandpass from 5$-$38 Å; see Figure 1. To constrain high-T plasma components and to measure resolved He-like and H-like lines of Mg, Si, S, and Ar, we included one of the MOS CCD spectra (Turner et al. 2001), but only above $\sim$1.4 keV. Since MOS was closed during the AB Dor observation, we used the corresponding EPIC PN data instead (Strüder et al. 2001).

3. Results and Interpretation

The flux ratios between Ne or O lines and the Fe XVII lines are much smaller in π^1 UMa and χ^1 Ori than in AB Dor or EK Dra (Figure 1a). This trend is difficult to explain with a broad EM distribution given that the maximum formation temperatures $T_{\rm m}$ of Ne IX and of Ne X bracket $T_{\rm m}$ of Fe XVII, *unless* the coronae differ in their elemental composition: the Fe/O and Fe/Ne ratios must increase toward lower-activity stars. The effect is not related to time variability or calibration. We show in Figure 1b a similar analysis for fluxed *Chandra* spectra (partly from the archive, and using standard matrices as provided by CXC), with similar line ratios.

A full spectral analysis with XSPEC (using the vapec code) corroborates our suggestion. Figure 2 illustrates elemental abundances relative to O, normalized with the photospheric abundance ratios (error bars represent formal fit 90% confidence limits). There is a clear trend from an inverse FIP effect in AB Dor

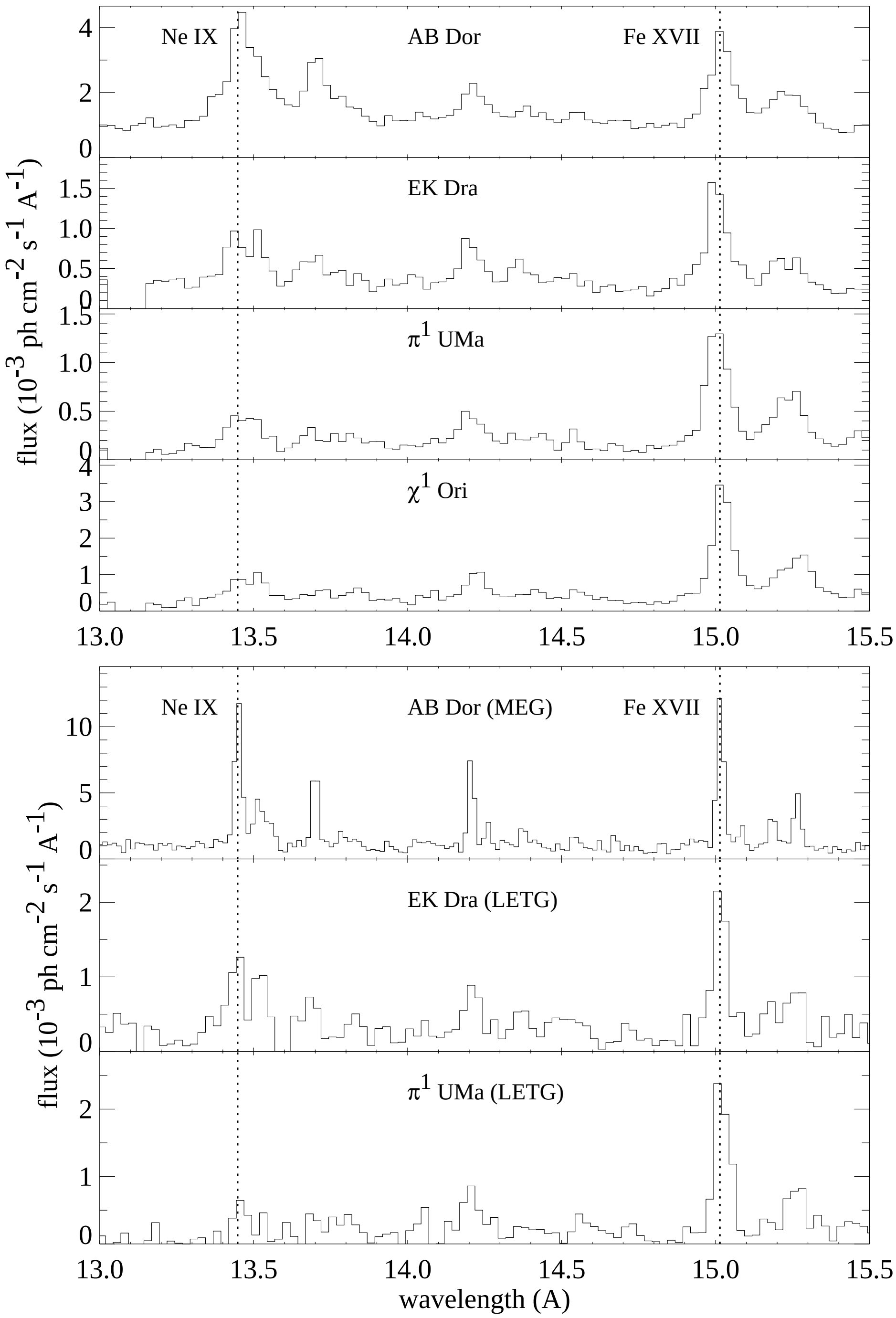

Figure 1. Fluxed X-ray spectra between 13−15.5Å of solar-type stars; the activity level decreases from top to bottom in each figure. **Top:** *XMM-Newton* RGS; **Bottom:** *Chandra* HETGS/MEG and LETGS. Two lines of Ne IX and Fe XVII are marked.

toward a normal FIP effect in π^1 UMa and χ^1 Ori. The Fe/O ratio clearly increases with decreasing activity, by about one order of magnitude. However, no trend is evident for the Ne/O ratio, which resides at values of $\approx 2-3$.

With the targets used for this study, we are not subject to uncertainty related to stellar composition and are led to the conclusion that the overall magnetic activity level alone governs the amount of FIP or IFIP bias. What could induce the anomalous suppression of low-FIP elements in active stars? We speculate that high-energy electrons could be important. Many magnetically active stellar coronae contain a large number of accelerated electrons detected by their gyrosynchrotron emission. While AB Dor is a prolific radio source (Lim et al. 1992), EK Dra's radio luminosity $L_{\rm R}$ is weaker by $\sim$one order of magnitude (Güdel, Guinan, & Skinner 1997), and for π^1 UMa, $L_{\rm R} < 0.003L_{\rm R}$(AB Dor) (Gaidos et al. 2000). If the electrons do not lose all their kinetic energy by radiation in coronal regions, there will be a net downward electron current into the chromosphere. The penetration depth $\ell \propto \epsilon^2/n_c$ for electrons of energy ϵ and a chromospheric layer of constant density n_c (Nagai & Emslie 1984). For $n_c = 10^{13}$ cm^{-3}, we obtain $\ell \approx 10^{17}\epsilon^2_{\rm keV}/n_c$[cm] $\approx 10-1000$ km for $\epsilon = 10-100$ keV, i.e., a significant fraction of the chromospheric thickness (after equation 13 in Nagai & Emslie 1984). We require a sufficiently small electron flux in order to balance the energy influx in particles by radiation before heating exceeds 10^5 K, i.e., to prevent explosive chromospheric evaporation. A charge separation is thus built up, together with an electric field that points downward. Protons and ions are consequently also driven downward, and the upper layers of the chromosphere from where the coronal material is ultimately supplied with material, becomes depleted of (typically singly ionized) low-FIP elements while (mostly neutral) high-FIP elements remain unaffected. Transport of the upper chromospheric layers into the corona by whatever means, e.g., microflares, will thus produce an IFIP biased coronal plasma. Only when the electron flux is large enough to produce explosive evaporation of a larger part of the chromosphere will the IFIP enrichment be quenched, i.e., the composition returns to near-photospheric, in agreement with observations of large stellar flares (e.g., Güdel et al. 1999).

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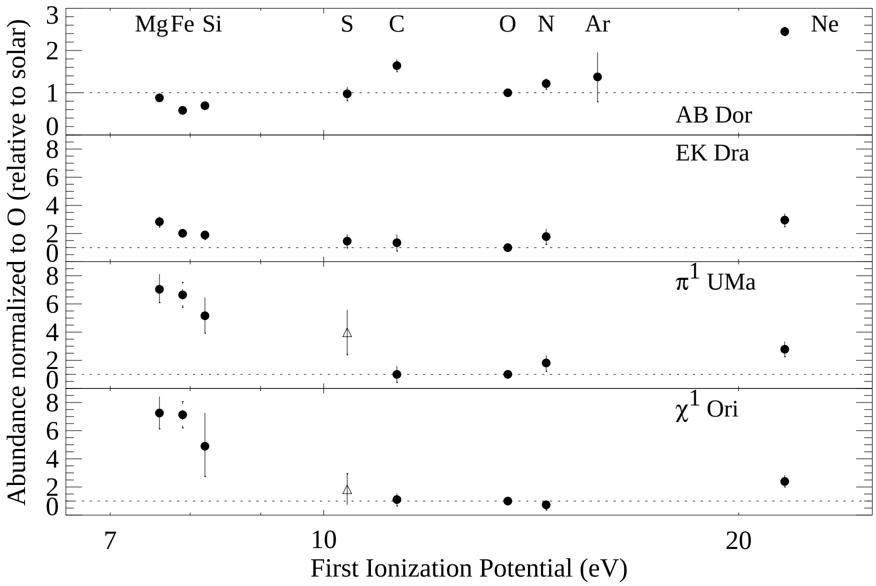

Figure 2. Elemental abundances in our four targets, shown as ratios with the abundance of O and normalized to the solar photospheric ratios, derived from fits in XSPEC. The triangles show estimates from individual weak lines (see Güdel et al. 2002 for further details).

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